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Assessment of the surface topography of Al 99.5% tubular products formed by cold flow forming technology

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Abstract

The process of cold flow forming (CFF) is a method of plastic deformation in which by using tools in the form of balls, rollers or flowforming wheel on special mandrel hollow cylindrical or conical parts, such as the various geometric combinations are obtained.

The technology is classified as a NSF technology ("net-shape forming") because it allows production of parts that are without any or with minimal subsequent modification of functional area and as such can be considered as a final product for installation. This paper shows an example of producing 99.5% Al tube workpieces by means of CFF technology. The analysis of the quality of the resulting outer surfaces by measuring the geometrical characteristics of profiles with special reference to the waviness outer surface of workpieces has been performed. The measurement was performed on 3D optical microscope.

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Key words: Cold Flow Forming, Al 99.5%, Workpiece waviness (waviness surface), optical microscope

1. Introduction

The process of cold flow forming (CFF) is a method of plastic deformation that using tools in the form of balls, rollers or flow forming wheel on special mandrel obtain hollow cylindrical or conical parts, such as the various geometric combinations, see Fig. 1. The aim of this procedure is to bring the material to the state of plastic flow and

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extrude it in the axial direction under the pressure of the rolls (two or three rolls). The result is the reduction of the diameter and the increase in length of the workpiece. The deformation occurs in a narrow contact zone between the rolls and the material. Because the material is mostly processed in cold state, the effect of its strengthening takes place, causing the improvement of its mechanical properties.

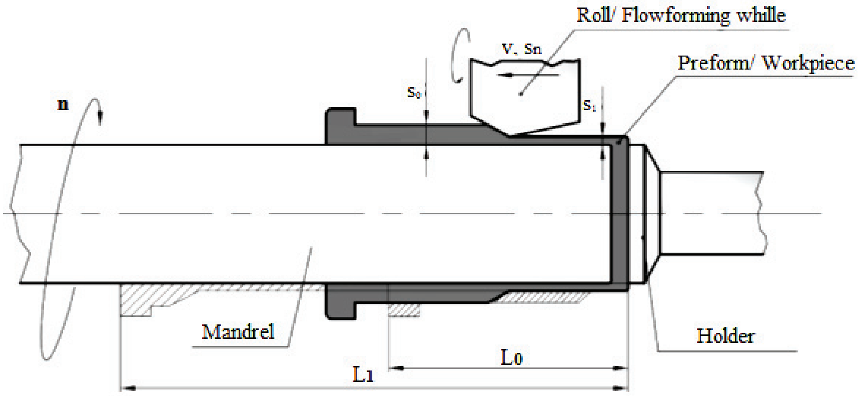
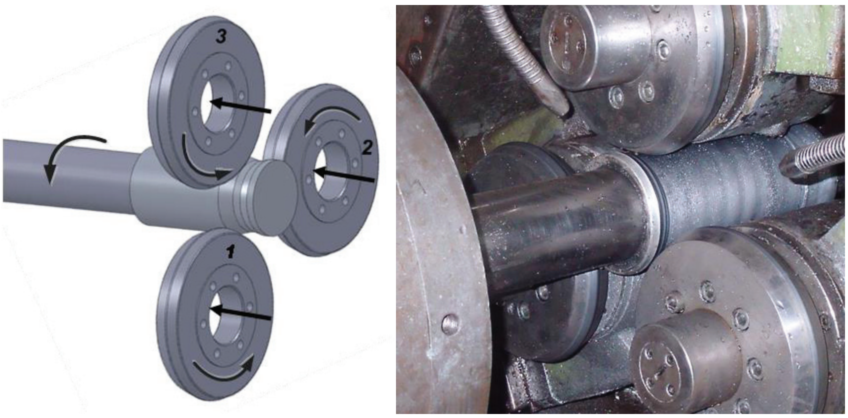


Fig. 1.Schematic representation of the forward cold flow forming [1].

The procedure of this technology is classified as a NSF technology ("net-shape forming") because it allows production of parts that are without any or with minimal subsequent modification of functional area. Therefore, the product can be considered as a final product for installation. Being very close to its final product shape, the processed parts need to have as less as possible surface defects or deteriorations. It is therefore important to know the surface quality of the parts made in relation to the input parameters of their forming method – CFF [3,4]. Here is important to highlight that the radius of the rolls as a key influential factor on the outer surface waviness has been kept constant during the experiment. The influence of the processing parameters, namely: the number of revolutions per minute (rpm), feed rate and degree of deformation on the surface characteristics has been investigated. Material of the workpiece is 99,5% aluminium. The qualities of the resulting outer surfaces have been expressed by measuring the geometrical characteristics of profiles with special reference to the waviness of the surface. The waviness is considered to be an important macro-geometrical characteristic of the surface. Its measurements were performed on 3D optical microscope MahrSurf TS50. Forming is performed by means of three rollswith corresponding radius of the rolls: R_1 = R_2= 4 mm and R_3 = 2 mm, see Fig. 2.



a) b)

Fig. 2. 3D model(a) and the real appearance of the tool and workpiece in forming by CFF technology(b)

2. Experimental work

In order to obtain net-shape final product of the preformed 99,5% Al workpiece (Figure 3) the forward cold flow forming – CFF technology has been performed in two stages. Those stages are related to dimensions of the workpiece before and after processing, see Fig. 3.

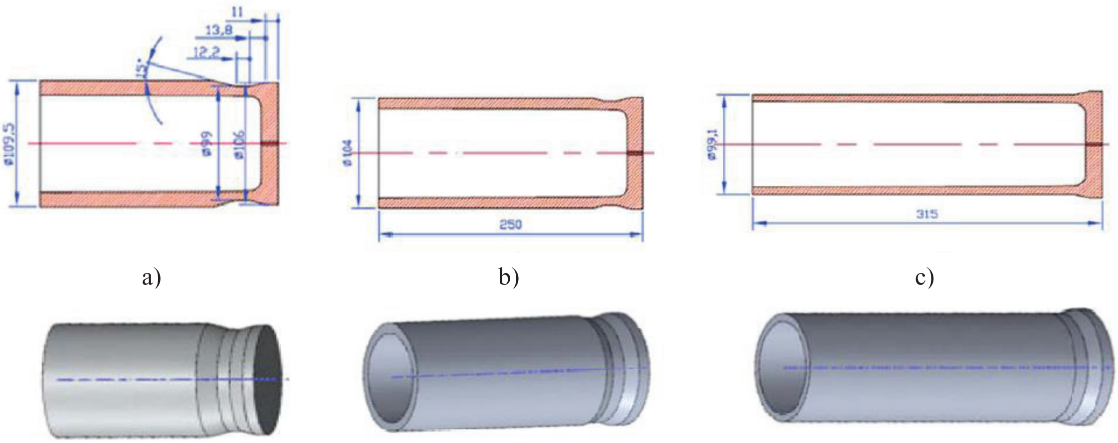


Fig. 3. The workpiece in the different stages of processing (a) Preform; (b) Workpiece after the phase I; (c) Workpiece after the phase II [2]

The experiment has been designed according to a full factorial experimental plan with 11 runs ($2k+n_0=23+3=11$) with three independently variable factors ($k=3$) and repeating the experiment in the central point of the plan – n_0. The variable (investigated) factors are as follows: rpm of the mandrel or workpiece, axial feed of the rolls and degree of deformation. The experimental stages (I and II) have been designed to gain final outer diameter of 99,1 mm. That means if in Stage I the degree of deformation is set on level (+1), the corresponding Stage II need to be followed with corresponding level of (-1). Natural and coded factor's levels are shown in Table 1. Plan matrix of the experiment is given in Table 2. Only the combination of those two levels will gain the final measure of 99,1 mm. The actual overall plastic strain during the processing is in the range 51 to 58 %, while the partial degrees of deformation at certain stages ranging between φ_I=15 % to 35 % i φ_{II}=16 % to 37 %. The total percentage of drawn length in both stages ranges from 36 % to 50 % (from L=74 mm to 104 mm) and total logarithmic degree of deformation along the length ranges from φ_{lmin}=0,27 to φ_{lmax}=0,59.

After each stage of the forming process the mechanical properties of the obtained workpieces have been measured. Those measuring confirmed existing of a material strengthening effects.

The maximum increase in the yield strength $Rp_{0,2}$was 32,5 % ($Rp_{0,2}$=106/80 [N/mm^2]) and tensile strength Rm for 15,4 % (Rm=113/98 [N/mm^2]. The reductions of elongation (A) of 21.5% (28/22) and contraction (Z)of 5.8 % (86/81) were also measured.

Measurement of geometric characteristics for surface was performed on 3D optical microscope at the Laboratory for Metal Cutting and Machine Tools (LORAM) at Faculty of Mechanical Engineering University of Zenica. Analysis of the results obtained by applying ODSCAD software 6.0 GFMesstechnik GmbH company from Berlin.

Forming of workpieces by stages were performed according to plan-matrix three factors design of experiment. Designations of the outer surface waviness of the workpiece measured values are: Wt_I – surface waviness of the workpiece formed in the first stage, Wt_{II}– surface waviness of the workpiece formed in the first stage.

Table 1.Fastor's levels

Factor		Natural	Coded
Rpm of the mandrel or workpiece,n, min-1	Top level	240	+1
	Basic level	190	0
	Bottom level	140	-1
Feed,s, mm/min	Top level	100	+1
	Basic level	80	0
	Bottom level	60	-1
Depth of forming (degree of deformation),Δs, mm (φ)	Top level	3.5	+1
	Basic level	2,75	0
	Bottom level	2	-1

Table 2. Plan-matrix and results of measurement

Run	Rpm mandrel,n	Feed,s	Depth of forming, I-first stages, ΔsI	Depth of forming, II-second stage, ΔsII	Outer surface waviness of the workpiece	
					WtI, μm	WtII, μm
1	-1	-1	-1	+1	35,4	83,4
2	+1	-1	-1	+1	41,3	89,6
3	-1	+1	-1	+1	157,2	162,7
4	+1	+1	-1	+1	60,9	135,9
5	-1	-1	+1	-1	42,4	85,6
6	+1	-1	+1	-1	23,4	77,4
7	-1	+1	+1	-1	151,9	113,9
8	+1	+1	+1	-1	35,4	95,6
9	0	0	0	0	60,2	107,7
10	0	0	0	0	55,4	118,4
11	0	0	0	0	44	108,4

Fig. 4 presents the appearance of the two workpiece surface (No.1, No.3) after the first processing stage and a graphical representation of the recorded surface topography.

The full report on the measurement of surface topography for one workpiece using the 3D optical microscope with all the characteristics of the surface is presented in Fig. 5. The same approach is used for all samples. From the reports the waviness values are extracted and used in further procedure (Table 2. columns 6 and 7).

Fig. 6.gives the preview of the surfaces for all experimental runs after first stage.

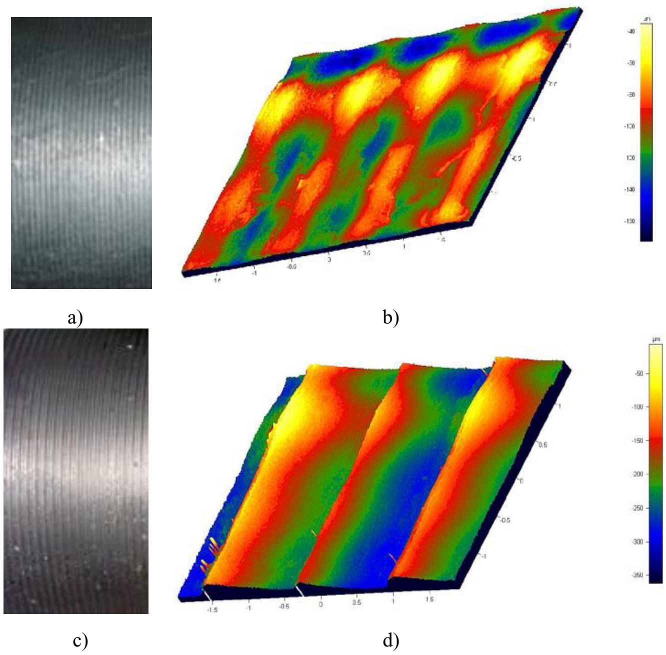
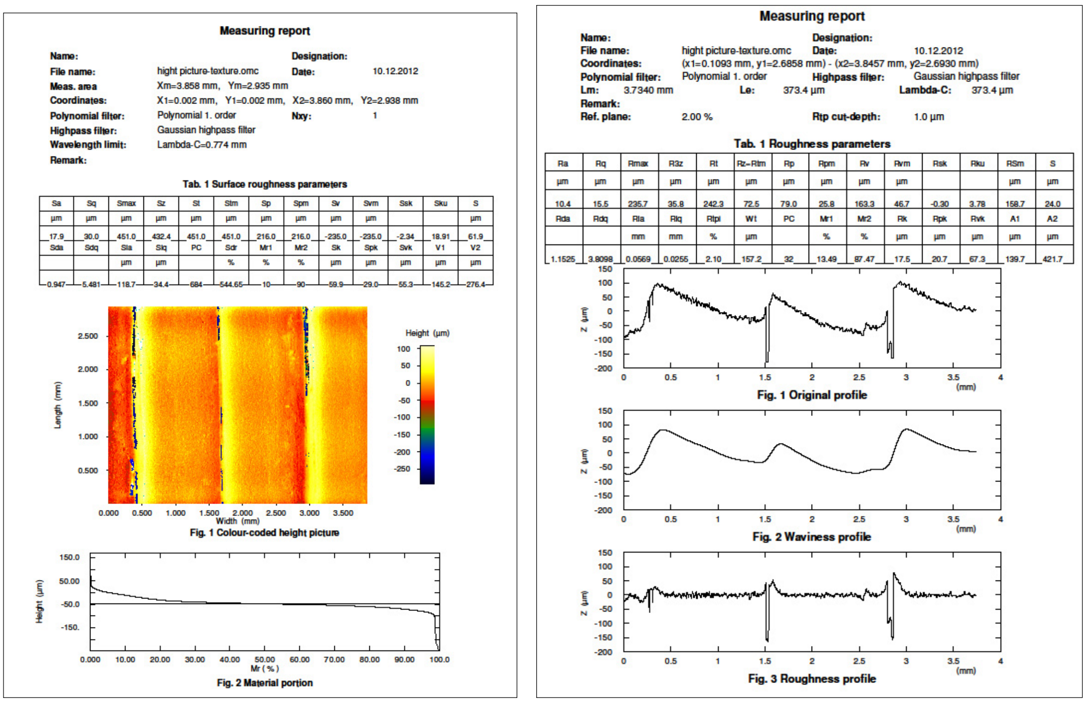


Fig. 4. Layout of the real surface of a workpiece (a, c) and display of surface topography (b,d) of two samples (No.1-a, b; No.3-c, d) after the first processing stage



Measuring report

Name:
Designation:
File name: hight picture-texture.omc
Date: 10.12.2012
Meas. area Xm=3.858 mm, Ym=2.935 mm
Coordinates: X1=0.002 mm, Y1=0.002 mm, X2=3.860 mm, Y2=2.938 mm
Polynomial filter: Polynomial 1. order
Nxy: 1
Highpass filter: Gaussian highpass filter
Wavelength limit: Lambda-C=0.774 mm
Remark:

Tab. 1 Surface roughness parameters

Sa	Sq	Smax	Sz	St	Stm	Sp	Spm	Sv	Svm	Ssk	Sku	S
µm	µm	µm	µm	µm	µm	µm	µm	µm	µm			µm
17.9	30.0	451.0	432.4	451.0	451.0	216.0	216.0	-235.0	-235.0	-2.34	18.91	61.9
Sda	Sdq	Sla	Slq	PC	Sdr	Mr1	Mr2	Sk	Spk	Svk	V1	V2
		µm	µm		%	%	%	µm	µm	µm	µm	µm
0.947	5.481	118.7	34.4	684	544.65	10	90	59.9	29.0	55.3	145.2	276.4

Fig. 1 Colour-coded height picture

Fig. 2 Material portion

Measuring report

Name:
Designation:
File name: hight picture-texture.omc
Date: 10.12.2012
Coordinates: (x1=0.1093 mm, y1=2.6858 mm) - (x2=3.8457 mm, y2=2.6930 mm)
Polynomial filter: Polynomial 1. order
Highpass filter: Gaussian highpass filter
Lm: 3.7340 mm **Le:** 373.4 µm **Lambda-C:** 373.4 µm
Remark:
Ref. plane: 2.00 %
Rtp cut-depth: 1.0 µm

Tab. 1 Roughness parameters

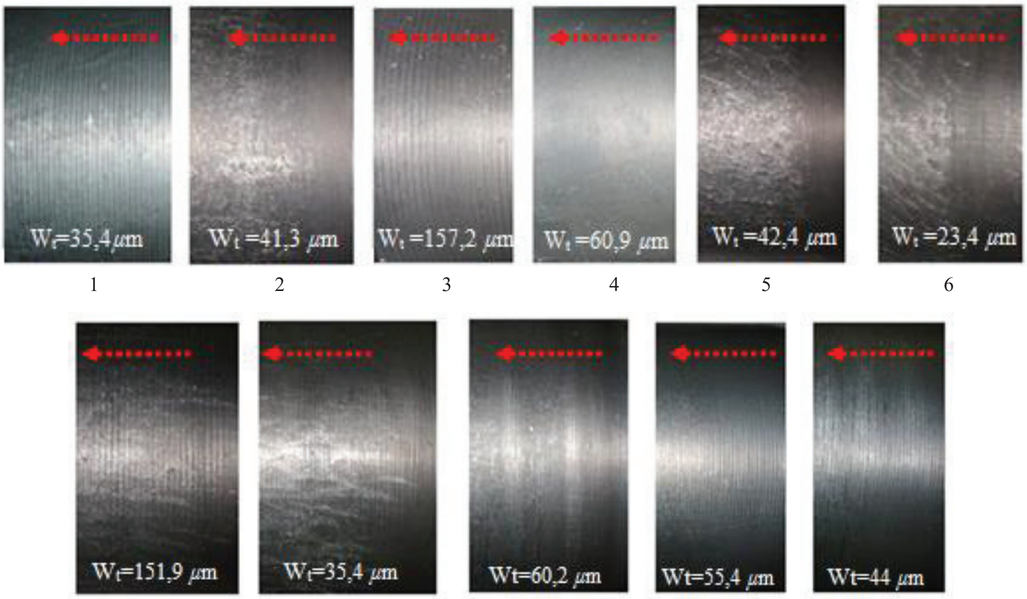
Ra	Rq	Rmax	R3z	Rt	Rz=Rtm	Rp	Rpm	Rv	Rvm	Rsk	Rku	RSm	S
µm	µm	µm	µm	µm	µm	µm	µm	µm	µm			µm	µm
10.4	15.5	235.7	35.8	242.3	72.5	79.0	25.8	163.3	46.7	-0.30	3.78	158.7	24.0
Rda	Rdq	Rla	Rlq	Rtpi	Wt	PC	Mr1	Mr2	Rk	Rpk	Rvk	A1	A2
		mm	mm	%	µm		%	%	µm	µm	µm	µm	µm
1.1525	3.8098	0.0569	0.0255	2.10	157.2	32	13.49	87.47	17.5	20.7	67.3	139.7	421.7

Fig. 1 Original profile

Fig. 2 Waviness profile

Fig. 3 Roughness profile

Fig. 5. The results of topography measurement for No.3 sample after first stage (3D optical microscope using the ODSCAD 6.0 software)



Note: 1-11- number of workpieces according to experimental design

Fig. 6. Layout of the real surface of a workpieces after the first processing stage (arrow indicates the direction of the axial feed tools, i.e. the direction of material extrusion)

3. Analysis of results

According to measured results it is possible to design diagram showed in Fig. 7. From this diagram is clearly visible that waviness of the surfaces obtained after Stage II is significantly higher than the corresponding (the same sample) waviness obtained after Stage I.

Fig. 8.shows the 3D diagrams of the waviness in relation to n, s and Δs obtained on the basis of the values in Table 2.

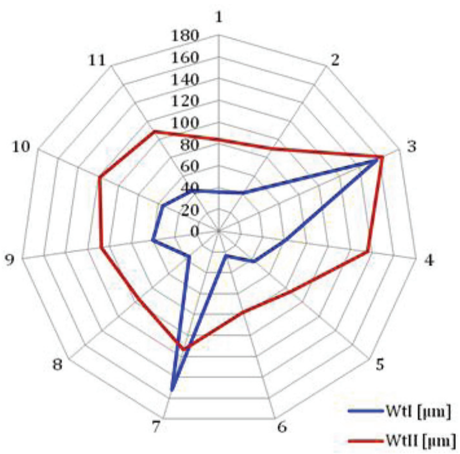
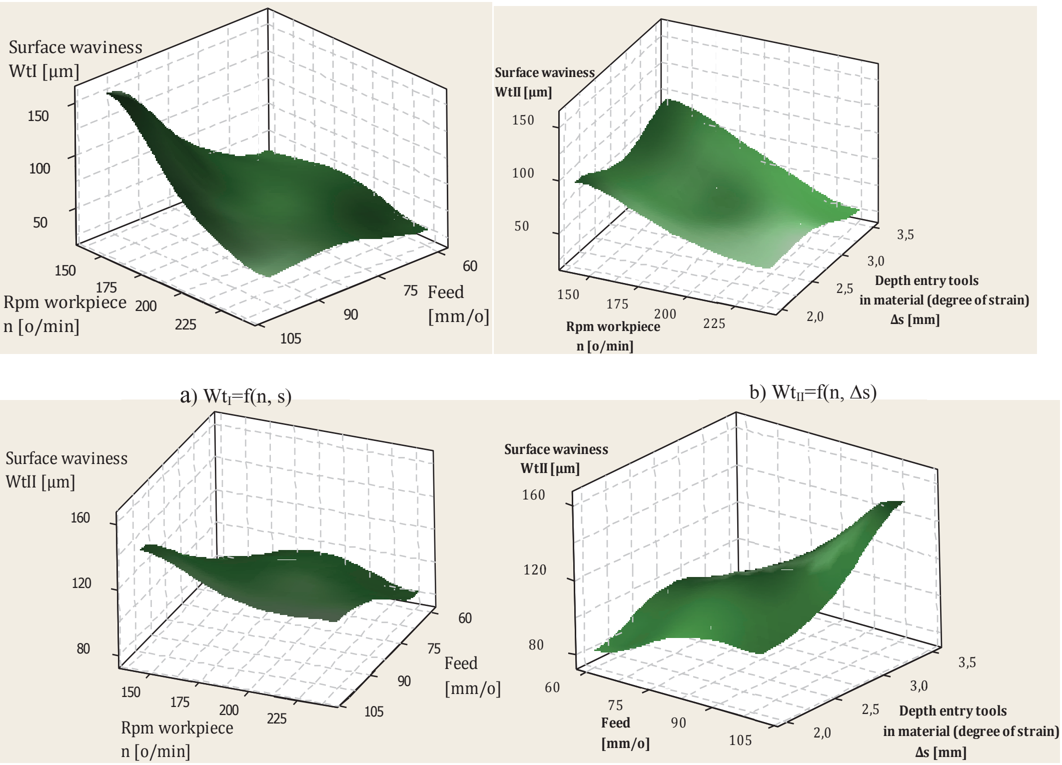


Fig. 7. Results of measuring waviness on the outer surface of workpieces (Wt_I –after Stage I waviness, Wt_{II}– after Stage II waviness)



a) $Wt_I=f(n, s)$ b) $Wt_{II}=f(n, \Delta s)$

c) $Wt_{II}=f(n, s)$ d) $Wt_{II}=f(s, \Delta s)$

Fig. 8. 3D diagrams of surface waviness in relation to forming parameters

It is observed that higher values of surface waviness were obtained by forming with a lower rpm of a mandrel, with higher values of feed and with bigger depth of forming.

This is also confirmed by the exponential mathematical model of the surface waviness in dependence of input parameter n, s, Δs. This model is obtained using design of experiment (DoE) and regression analysis:

$$W_t(n,s,a)=39,44.n^{-1,32}.s^{1,75}.\Delta s^{-0,43},\ \mu m \quad (1)$$

Where:
n, rpm mandrel or workpiece, min^{-1}
s, feed, mm/min
Δs (φ), depth of forming (degree of strain), mm.

Conducted research indicates that the highest value of waviness are reached for sample 3 and sample 7.

Comparing the average waviness values obtained for different depth of forming (samples 1-4, samples 5-8 and samples 9-11) one can conclude that the minimal waviness is obtained for samples group 5-8 (78.2 µm). The result suggests that best approach to perform flow forming process is to start with higher depth of forming in the first pass (stage I) then the lowering depth of forming in next stage. In opposite case, the obtained average waviness was 95.8 µm (samples 1-4). For the balanced depth of forming (same values in first and second stage – central experimental point –samples 8-11) the obtained average surface waviness was 82,4 µm.

4. Conclusions

Finally, according to above presented results, the following can be concluded:

- In addition to the radius of the rolls, which was not the subject of this research, the parameters of forming process: n-rpm mandrel or workpiece, s-feed-and Δs or φ-depth of forming or degree of strain, are playing an important role in controlling final workpiece surface parameters (waviness),
- Extreme values of the waviness of the workpieces were obtained for samples no. 3 and 7. Both of them were characterized by working with a maximum feed of tools (rolls). This fact is confirmed by regression analysis, equation (1), in which the feed is detected as the most influential controlling parameter in this experiment.
- To decrease the waviness of the surface of workpieces processed by means of flow forming technology the smaller feeds and depths of forming, as well as the higher speed of tool (workpiece) rotations need to be applied,
- Better quality of the surface or less waviness is obtained if the first operation, with the higher depth of forming, is followed with the smaller forming depths in the second operation.

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